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Reciprocating Compressor Protection and Management

Considerations When Evaluating Unfiltered Piston Rod Vibration
for Automatic Shutdown on API-618 Reciprocating Compressors

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Introduction

End users have applied proximity probe measurements at the piston rod on API-618 style reciprocating compressors for over four decades. Early monitoring systems interpreted the unfiltered piston rod vibration signal generated by the probes as a rod drop measurement. More modern systems interpret the unfiltered piston rod vibration signal as rod position or as segmentally analyzed vibration. In any case, end users usually want an automatic shutdown from these probes. Experience has shown that alarms, which indicate changes in machine condition, have value¹; however, connecting the probes to an automatic shutdown system does not result in accurate and reliable operation.

Automatic shutdown systems have only one task: shut down the machine when serious damage may occur. For all other loads, conditions, transients, etc. the automatic shutdown system must not initiate a false trip. Use of unfiltered piston rod vibration data can cause an automatic trip system to shutdown falsely and to miss critical events.

The intent of this paper is to summarize industry experience that supports the above conclusion.

False Trip

In the fall of 2009, reference (3) stated:

- “Using rod run out as a shut down parameter, it is possible to detect the development of a piston rod crack (possibly not detectable with vibration) and successfully trip, before it fails completely.”
- “Automated machine monitoring systems with rod position shutdown functions lead to lower cost of production and higher plant efficiency.”

The above conclusions seem surprising, given that this case history derives from a machine operated at 170% of OEM recommended rod load. Such a condition does not represent common operating practice in the refining and petrochemical industries. This paper presents a series of case histories using data from API-618 machines operated within OEM limits and guidelines.

This first example has previously been presented in the context of rod drop and rod position measurement². The machine instrumentation included three pairs of orthogonal probes: one pair at the pressure packing case, one pair at the intermediate packing case, and the third pair at the scraper packing case.

An analysis of the 1st stage cylinder shows that, in fact, segmental vibration analysis does not reliably correlate with machine condition. This data set was acquired as the unit began to increase flow through the compressor. At 17:40 the plant loaded the compressor to 100% from 50%. Figure 1 shows the piston rod vibration at 17:48:21, eight minutes after this load change.

1. The scope of this paper does not include hyper compressors found in low-density polyethylene service. On those machines, which employ a solid tungsten carbide plunger, shutdown on unfiltered plunger vibration has provided a reliable automatic shutdown system. It remains a strongly recommended protection parameter for those machines.

2. Others have inaccurately referred to the data in Figure 1 as “Piston Rod Position” (see reference 3). Anytime a squiggly line representing displacement, velocity or acceleration shows changes over very short time periods (i.e. one to eight revolutions), vibration properly describes the signal. Rod drop, rod position, segmental vibration analysis, etc. all refer to characteristics derived from the vibration data.

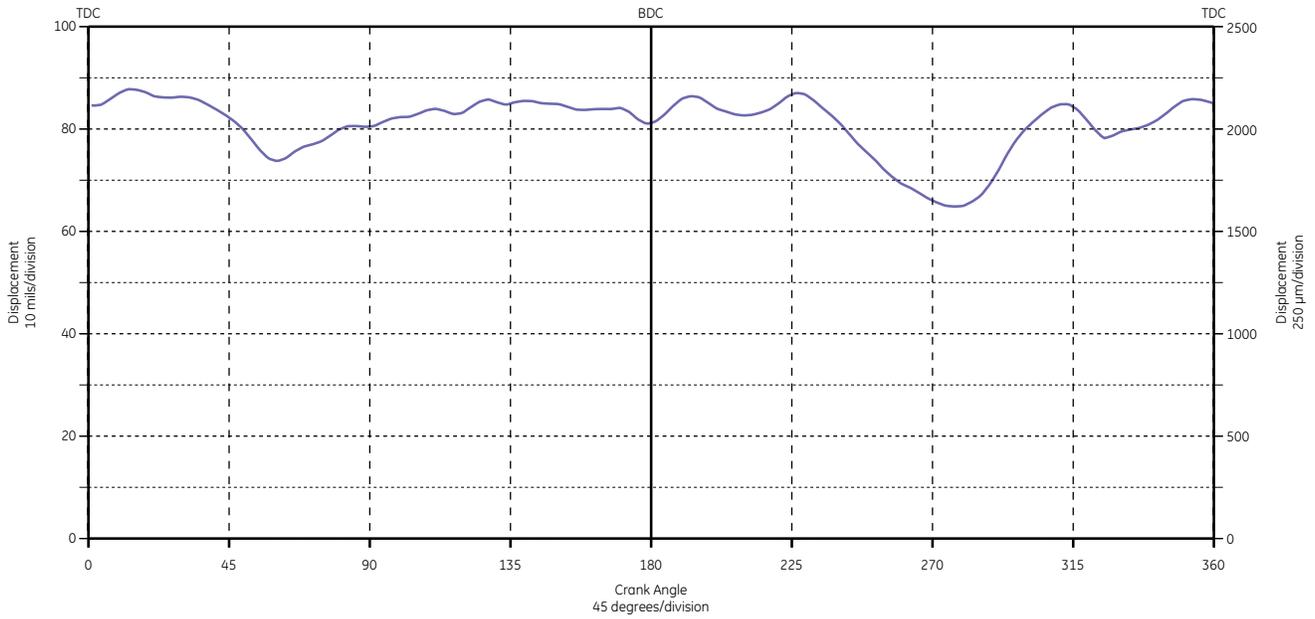


Figure 1. Stage 1 True vertical probe unfiltered piston rod vibration at 17:48:21.

Calculation of the peak-to-peak values within eight equally spaced segmental bands can readily be accomplished and added to the data of Figure 1. Figure 2 shows these segmental bands, indicated by the green boxes at the bottom, along with the original waveform. The bands have been scaled to the vertical axis.

Reference (3) states that normal peak-to-peak trip limits should be set at 800 to 900 μm (31 to 35 mils). The reference does not provide guidance on which one to select. To be conservative and reduce risk of harm, the lower limit of 800 μm (31 mils) has also been drawn on Figure 2.

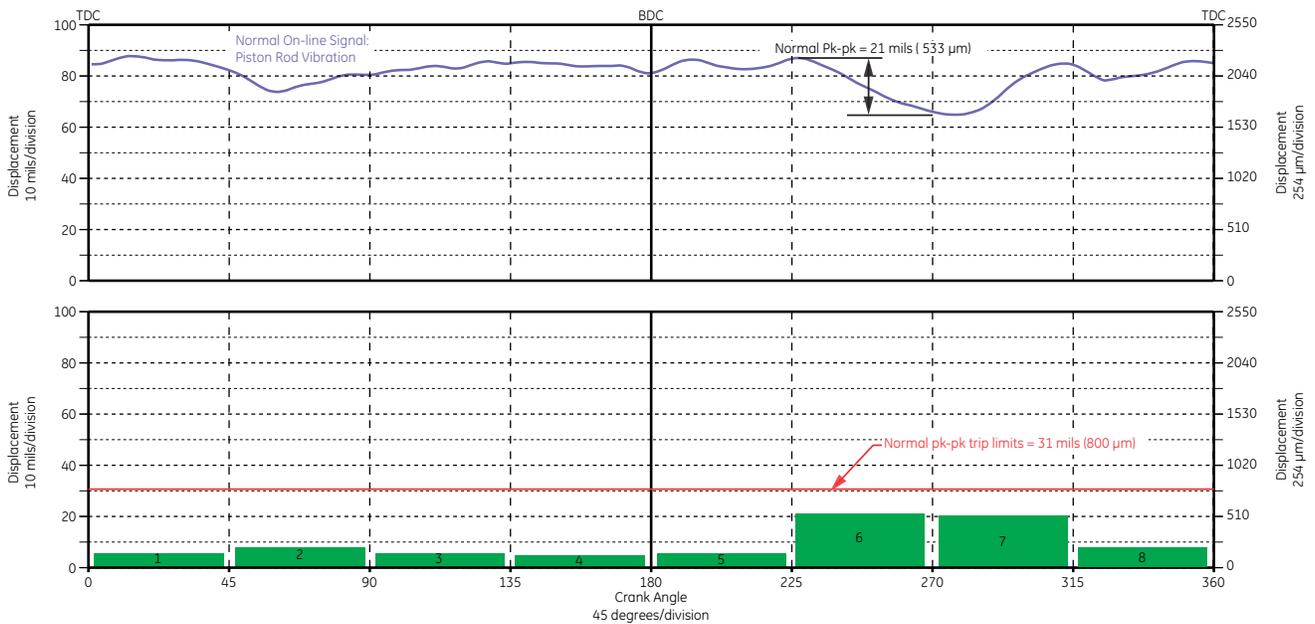


Figure 2. Stage 1 True vertical probe unfiltered piston rod vibration at 17:48:21 (top) with segmental vibration analysis (bottom).

As the compressor continues to operate, the piston, cylinder, and packing case all begin to reach thermal equilibrium with the new load step. This takes a little more than one hour. Figure 3 shows the trend of segment 6 and segment 7 over this equalization period. Note that this time period of Figure 2 roughly equals the

length of time presented on page 13 of reference (3). At 18:53:21 the segment trend crosses the shutdown limit³ and would result in an automatic machine shutdown. In this case, the shutdown would have occurred as a result of normal machine operation rather than from a machine malfunction such as a cracked piston rod.

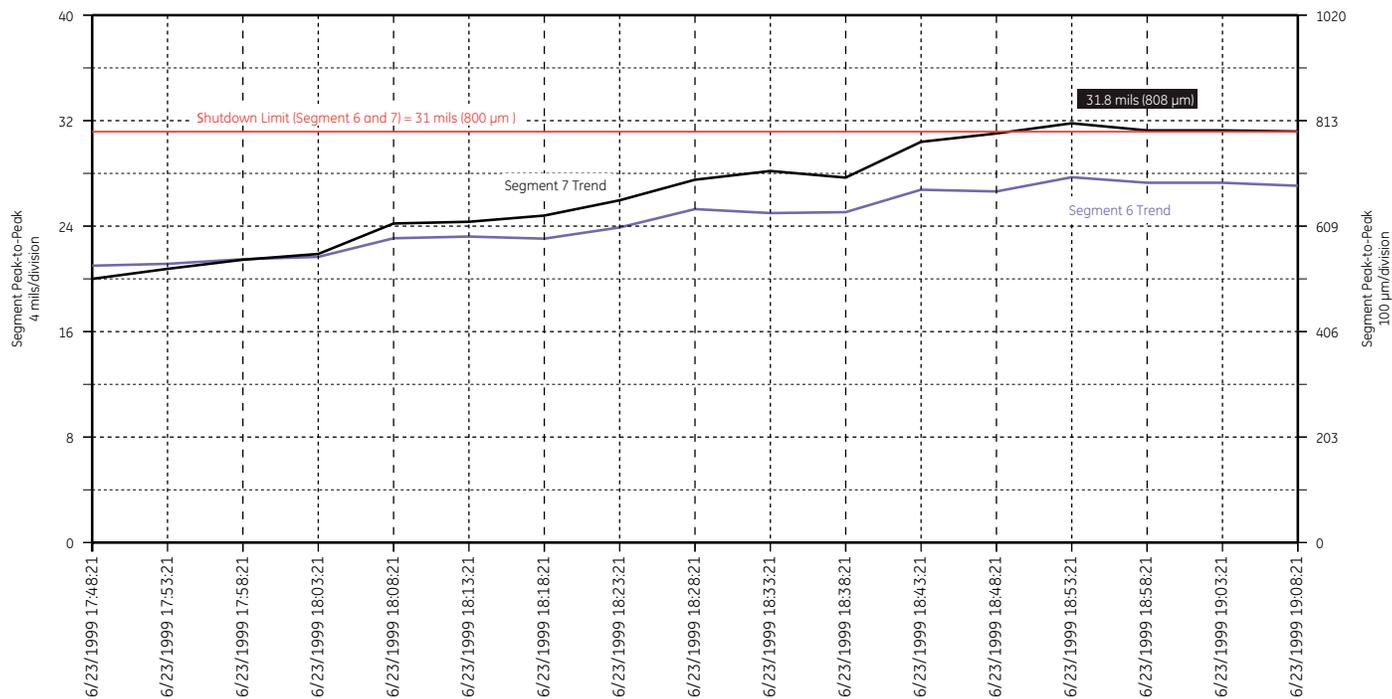


Figure 3. Segment 6 and segment 7 trends (evening of June 23, 1999).

3. The term "shutdown limit" is referred to as "safely limit" in reference (3).

With the events in Figure 3 known, the shutdown limits could be adjusted to avoid this situation in the future. Reference (3) suggests a fairly broad range of values, so for segment 6 and segment 7, the new shutdown limit could be 35 mils (900 μm).

Figure 4 shows these revised values. These values make more intuitive sense and better leverage the segmental structure for alarming and automatic shutdown.

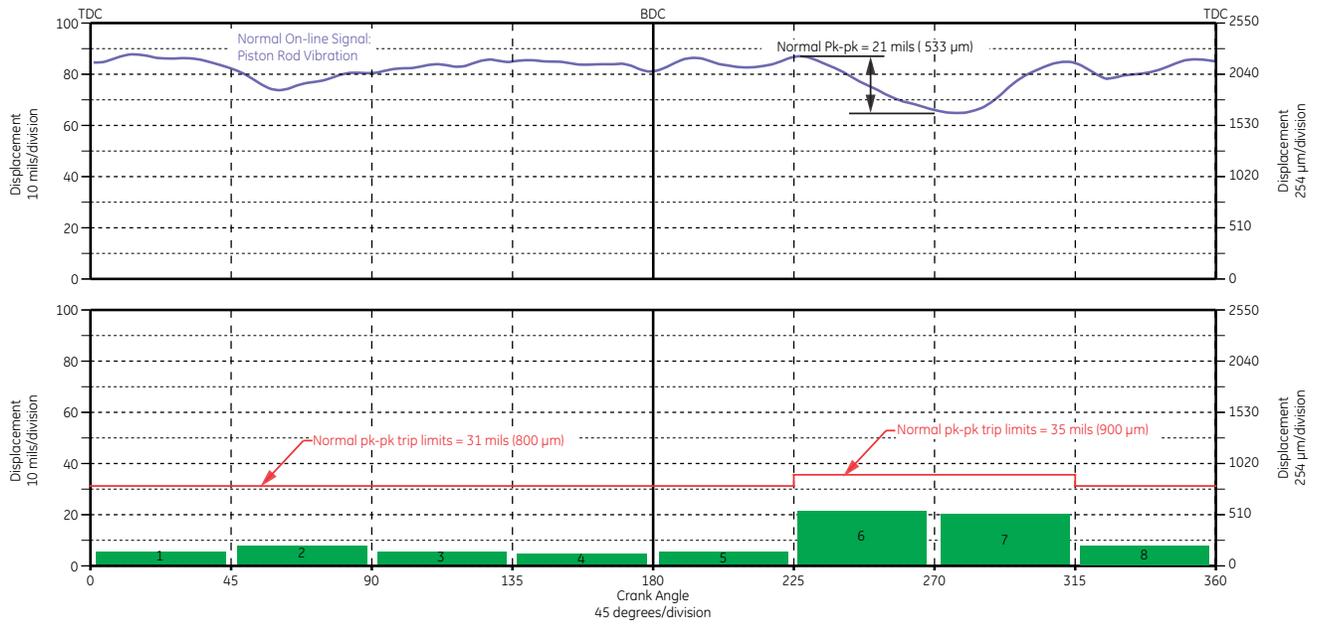


Figure 4. True vertical unfiltered piston rod vibration at 17:48:21 with segmental bands and higher shutdown limit.

With new operational shutdown limits in place, the compressor could continue to operate. In this particular case, the compressor continued to run for the next 18 hours. In the morning, as the sun came up and the ambient temperature began to rise, the level of piston rod vibration began to change. As shown in Figure 5, the

variation would cross the new shutdown threshold for segment 7. This would have resulted in an automatic shutdown. Figure 6 shows the crank angle domain data, which confirms the large amplitude at segment 7.

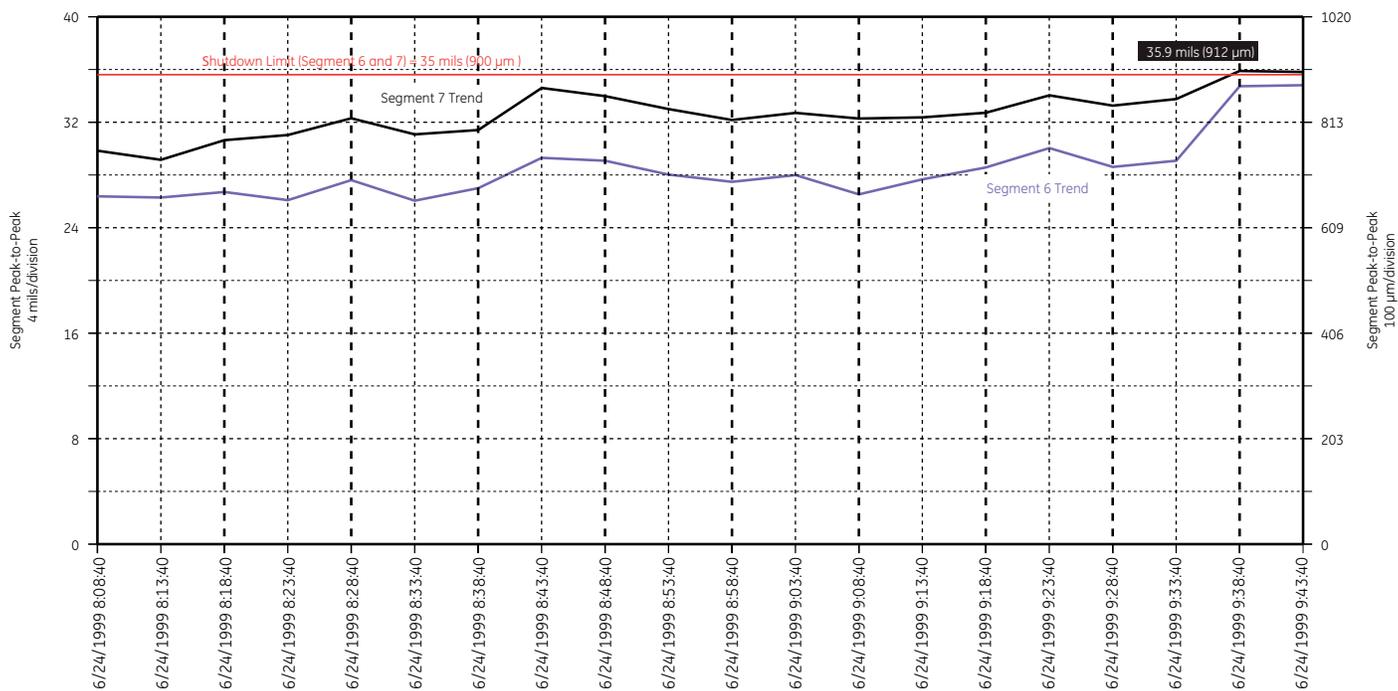


Figure 5. Segment 6 and segment 7 trends (morning of June 24, 1999).

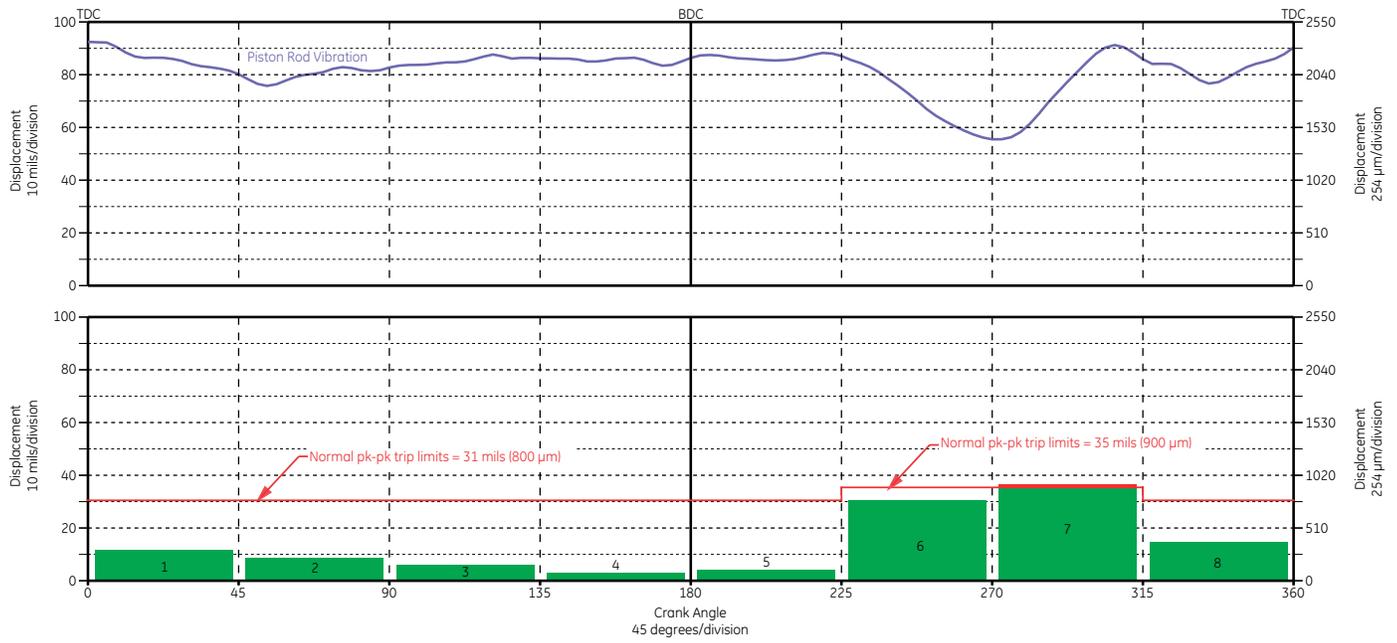


Figure 6. True vertical unfiltered piston rod vibration (June 24, 1999 at 09:38:40) with segmental bands and higher shutdown limit.

Clearly, establishment of proper segmental alarms for this load step requires additional run time and data analysis. Proper configuration of the rod drop monitor on this throw required an additional two days of run time. As the thermal transients appear to have a similar effect on the segmental vibration limits, it would likely require a similar effort to properly configure the segment limits at this load step. Furthermore, this effort would be required at each additional load step and would likely result in a different set of segment limits for each load step.

Parametric changing of the segmental shutdown limit values with both load steps and malfunctions⁴ could improve performance; however this paradigm results in a fragile protection system. This compressor utilizes pneumatic unloaders, so the protection system requires a link to the Distributed Control System (DCS) to read each load step. This effectively makes the cable, DCS communications gateway, and load table within the DCS an integral part of the shutdown system. Any Safety Integrity Level (SIL) evaluation would need to account for this architecture, as failure or error in these components will greatly reduce, or possibly eliminate, the automatic shutdown system.

Less clear is what strategy could accommodate the thermal transients during load steps. Excessively long alarm delays to avoid false trips could allow a real machine problem to quickly degrade, resulting in a missed trip. However, establishing the new thresholds at the time of load change would result in false trips.

Missed Trip – Loose Piston

False trips involve risks associated with starting and stopping the process. A more serious condition exists when a machine begins to experience significant mechanical degradation and the automatic shutdown system does not detect the problem.

The following case history has been published in reference (4). The reader should consult this article for a complete discussion of the data and analysis. Figure 7 shows one of the piston rod vibration waveforms, the associated segmental vibration values, and the lower limit suggested by reference (3). The figure shows that none of the segments reach the suggested shutdown limit. In this case, the automatic protection system would have failed to issue either an alarm or a shutdown (i.e. a missed trip).

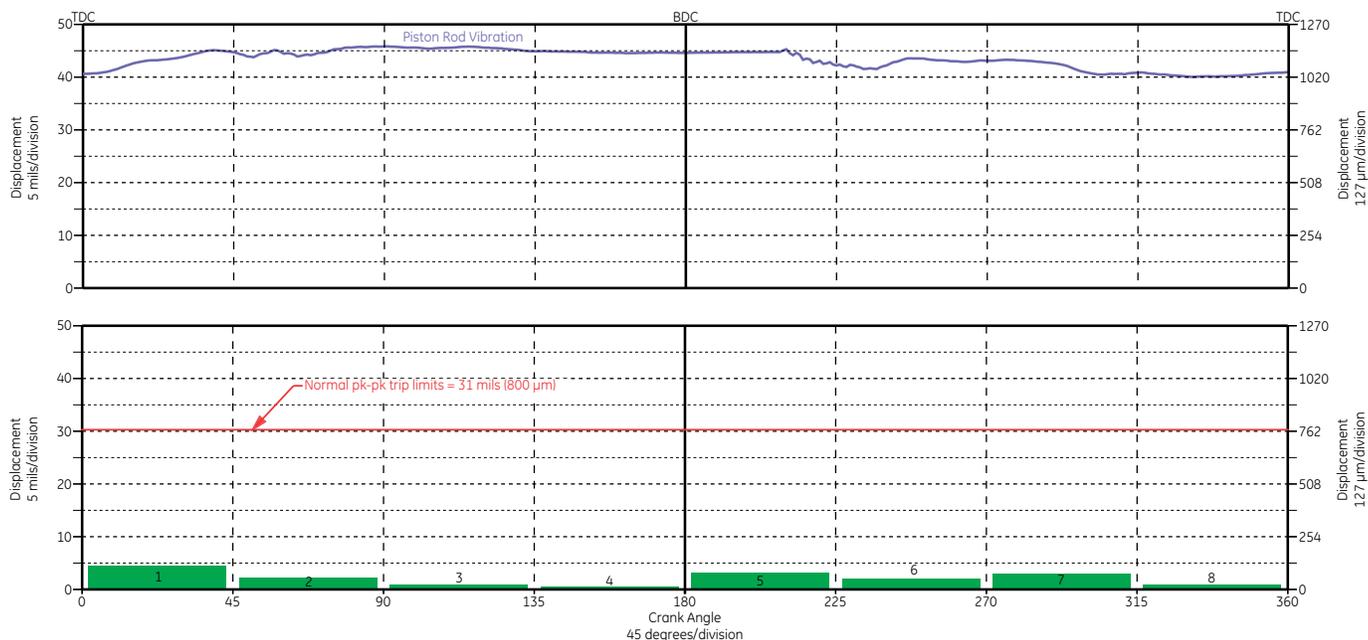


Figure 7. True vertical probe unfiltered piston rod vibration and segmental vibration at time of confirmed loose piston.

4. Parametric variation of the segmental vibration shutdown limits would also require consideration of the various failure modes. For example, a failure of piston rings on the 2nd stage cylinder alters the compression ratio across both 1st and 3rd stage cylinder as well as the inlet temperature to the 3rd stage cylinder. This failure would have an associated thermal transient that differs from the thermal transient associated with normal loading and unloading of the 2nd stage cylinder.

Figure 8 shows the piston rod vibration after the repair and return to service. The waveform appears very similar to the one in Figure 7. A comparison of the segment values in Figure 8 to those in Figure 7 shows that all values remain below 5 mils. The close similarity in waveforms during the event and after the repair

confirms that an automatic protection system configured to use segmental vibration analysis on the unfiltered piston rod vibration signal would have failed to issue either an alarm or an automatic shutdown on this event.

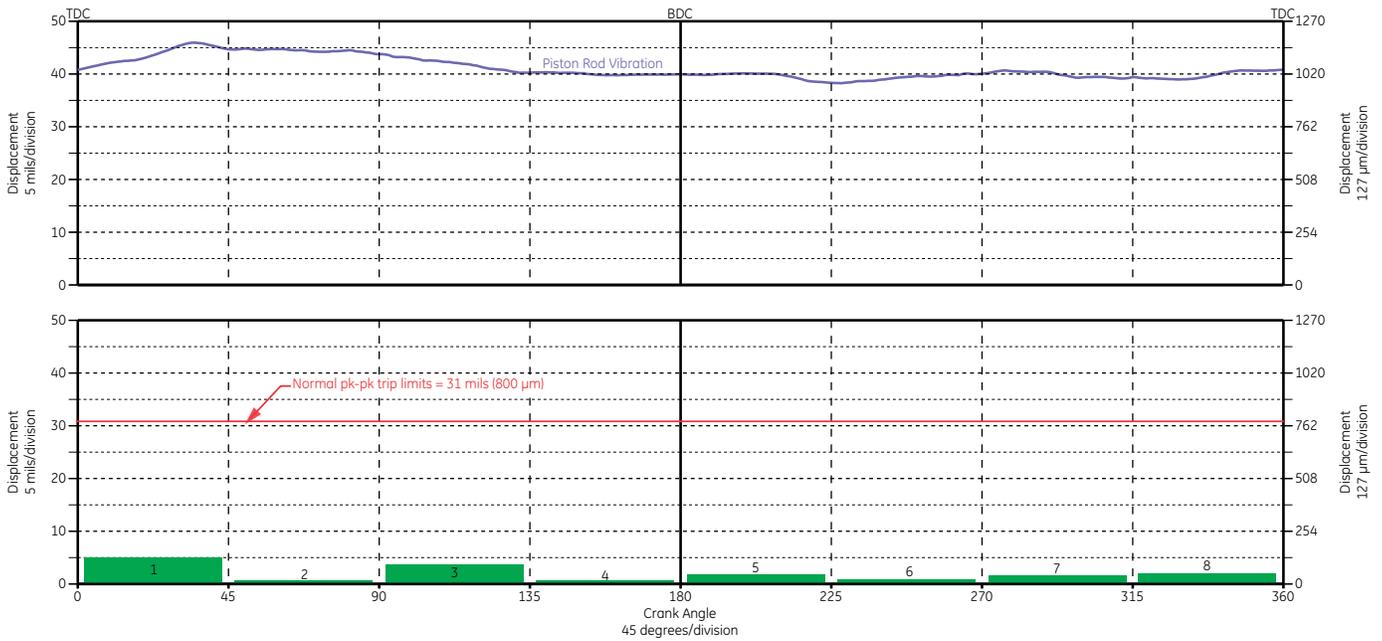


Figure 8. True vertical probe unfiltered piston rod vibration and segmental vibration analysis after repair.

Although the scope of this paper focuses on analysis of unfiltered piston rod vibration, one cannot help but to ask: what did the other transducer, in particular the crosshead acceleration, show? Figure 9 shows the filtered crosshead acceleration data. Two large events can readily be seen, the first at 55° and the other at 215° in the waveform. The events have an amplitude level of nearly 1.0

Gs 0-pk and track closely with the reversals within the gas rod load curve. In contrast, filtered crosshead acceleration data taken after the repair, shown in Figure 10, shows no large events. The filtered crosshead acceleration data provides a better indication of machine health.

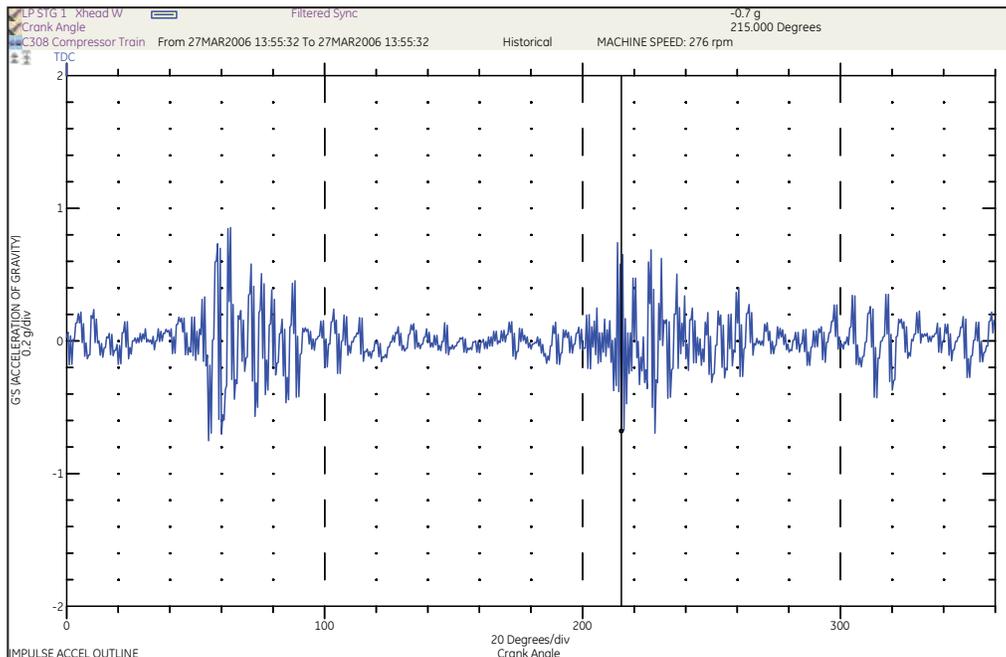


Figure 9. Filtered crosshead acceleration signal, confirmed loose piston.

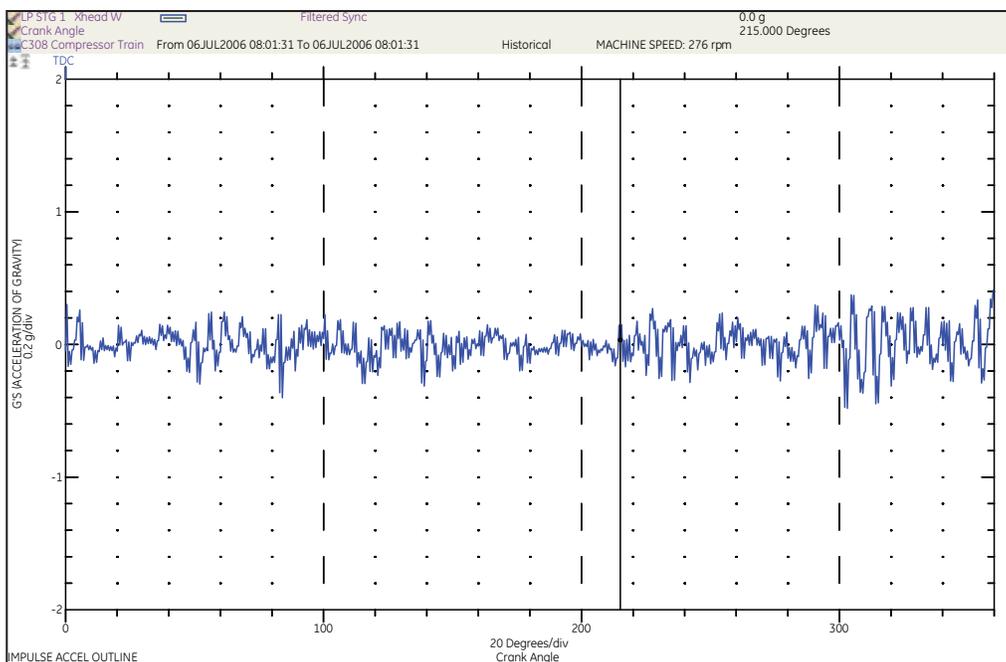


Figure 10. filtered crosshead acceleration signal, after repair.

Missed Trip – Broken Piston Nut Washer

The previous section explored the segmental vibration to a loose piston. This section explores the results of segmental analysis of piston rod vibration in the instance of a broken piston nut washer.

Approximately three months after return to service from an overhaul, plant personnel observed erratic piston rod vibration on the stage 1 LP cylinder. Figure 11 shows a sample of the data from this period with the alarm limits as suggested by reference (3). Segments 2 and 5 show the highest level of vibration.

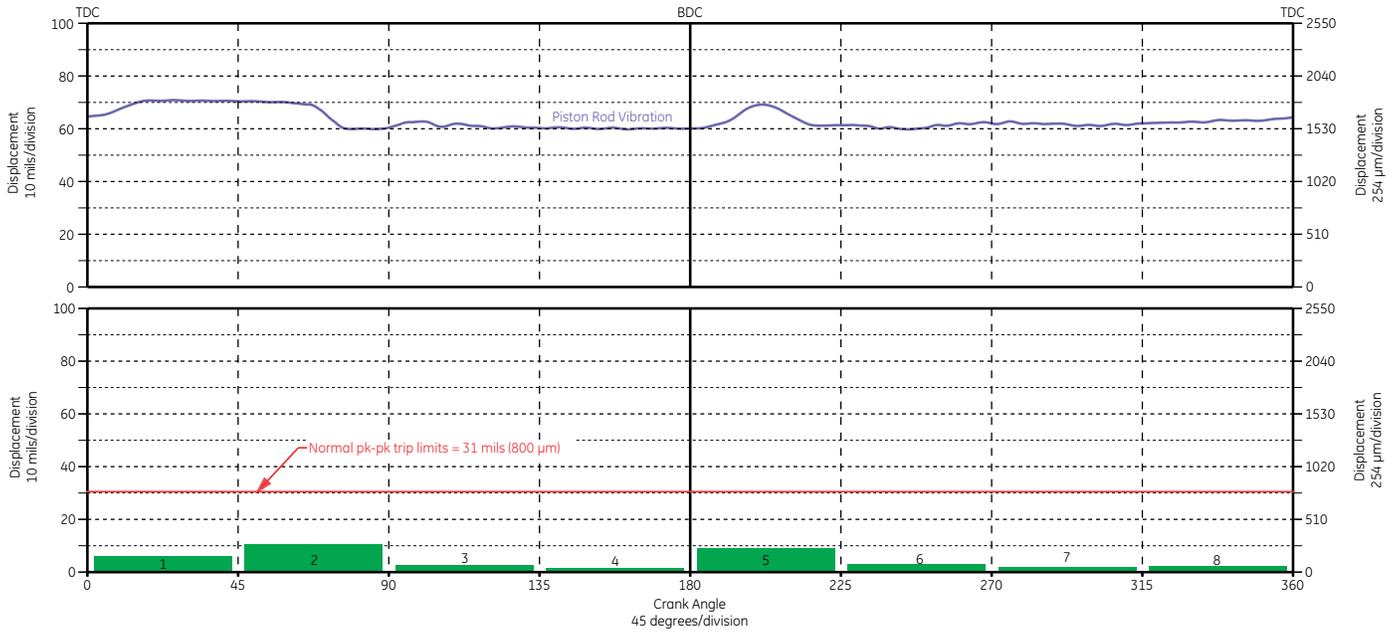


Figure 11. Stage 1 LP cylinder at 66% capacity vertical probe unfiltered piston rod vibration and segmental vibration analysis (September 2, 2007, 05:10:51).

Over the next several weeks, the plant continued to operate the compressor at 66% capacity while System 1* software collected data from the rod position probes. Table 1 summarizes the overall

peak-to-peak values as well as the segmental vibration values. As can be seen, the overall peak-to-peak values and the segmental band values change erratically over this time period.

Table 1. Stage 1 LP cylinder at 66% capacity. True vertical probe unfiltered piston rod vibration peak-to-peak values.

Waveform Time/Date	Unfiltered pk-pk	Band 1 pk-pk	Band 2 pk-pk	Band 3 pk-pk	Band 4 pk-pk	Band 5 pk-pk	Band 6 pk-pk	Band 7 pk-pk	Band 8 pk-pk
9/2/2007 5:10	11.14	6.13	10.65	2.70	0.83	9.05	2.76	1.78	2.42
9/5/2007 4:29	12.68	5.78	6.27	3.21	0.77	8.39	5.83	2.33	1.48
9/12/2007 14:56	10.42	2.49	3.06	4.14	0.86	5.77	7.43	3.93	1.20
9/13/2007 8:18	18.39	8.64	14.91	3.40	0.65	9.86	6.76	1.80	3.41
9/18/2007 1:24	17.84	5.88	6.90	2.46	0.76	11.44	13.07	4.65	1.33
9/23/2007 5:01	10.94	3.07	4.73	3.67	2.40	4.81	7.60	3.59	1.02
9/24/2007 5:01	11.72	2.79	4.22	3.85	2.23	5.46	8.14	3.34	1.14
9/25/2007 5:01	12.51	3.51	4.97	4.74	1.40	6.51	8.23	3.73	1.05
9/25/2007 11:11	12.31	3.19	6.23	4.53	1.34	6.36	6.61	3.01	1.95

Interestingly, the last row of data, shown in Figure 12, has lower segmental values than the initial data set of Figure 11, with all values well below 10 mils (255 μm). The decrease in segmental band values might erroneously be associated with an

improvement in machine condition. The contrast between Figure 11 and Figure 12 illustrates the difficulty in assessing machine condition from segmental analysis of piston rod vibration alone.

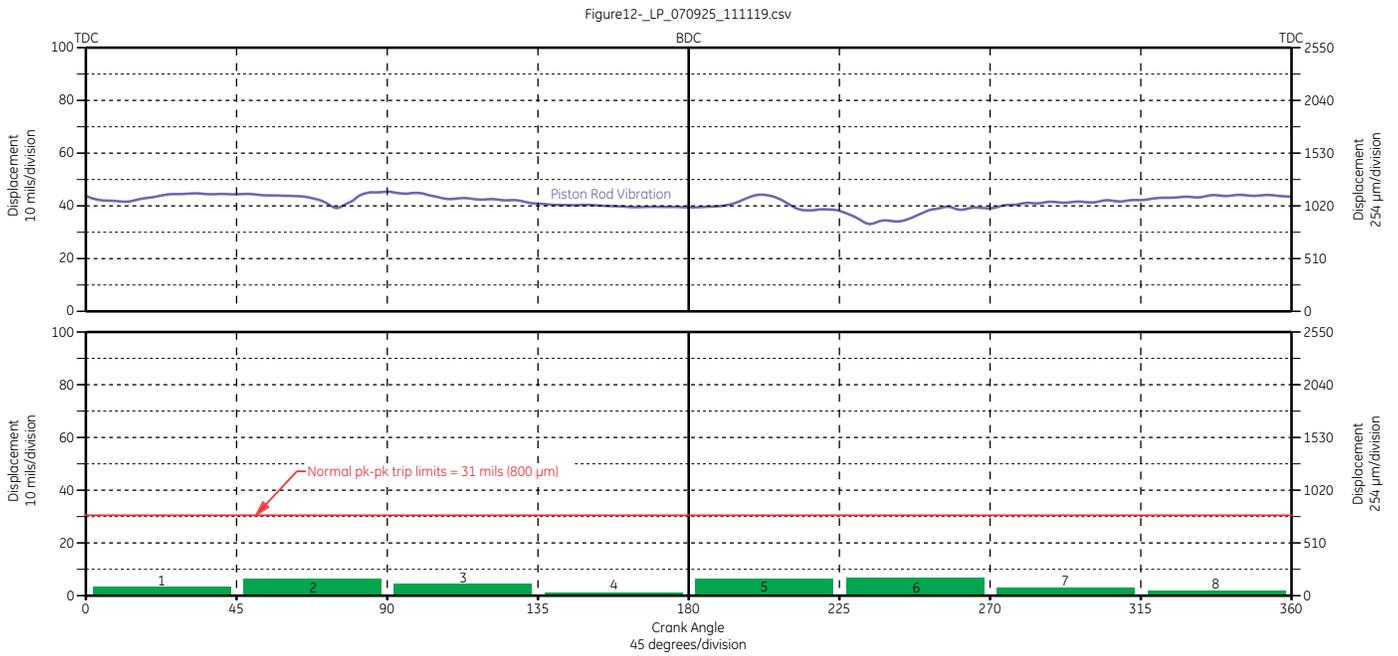


Figure 12. Stage 1 LP cylinder at 66% capacity vertical probe unfiltered piston rod vibration and segmental vibration analysis (September 25, 2007, 11:11:19).

At this point neither the crosshead acceleration nor the frame velocity indicates any impulse events, so the plant continued to operate the compressor and used System 1 software and the Bently Nevada* 3500 Machinery Protection System to continuously monitor the Stage 1 LP cylinder. At approximately 11:15 on September 25th, the plant increased the flow through the compressor to 100% and continued operations. At the end of February, 2008 the low frequency crosshead acceleration trend began to increase. An audible knock and advice to shut down

the machine, from both the Services team at GE Measurement & Control and outside consultants, convinced the plant to take an unscheduled outage to inspect the piston and running gear. On March 11th the plant shut down the compressor. The inspection found a broken piston nut washer. However, as Figure 13 shows, none of the segmental vibration values had reached the normal peak-peak value for trip recommended by reference (3). This result strongly suggests it is very difficult to assess machine condition from piston rod vibration segmental analysis alone.

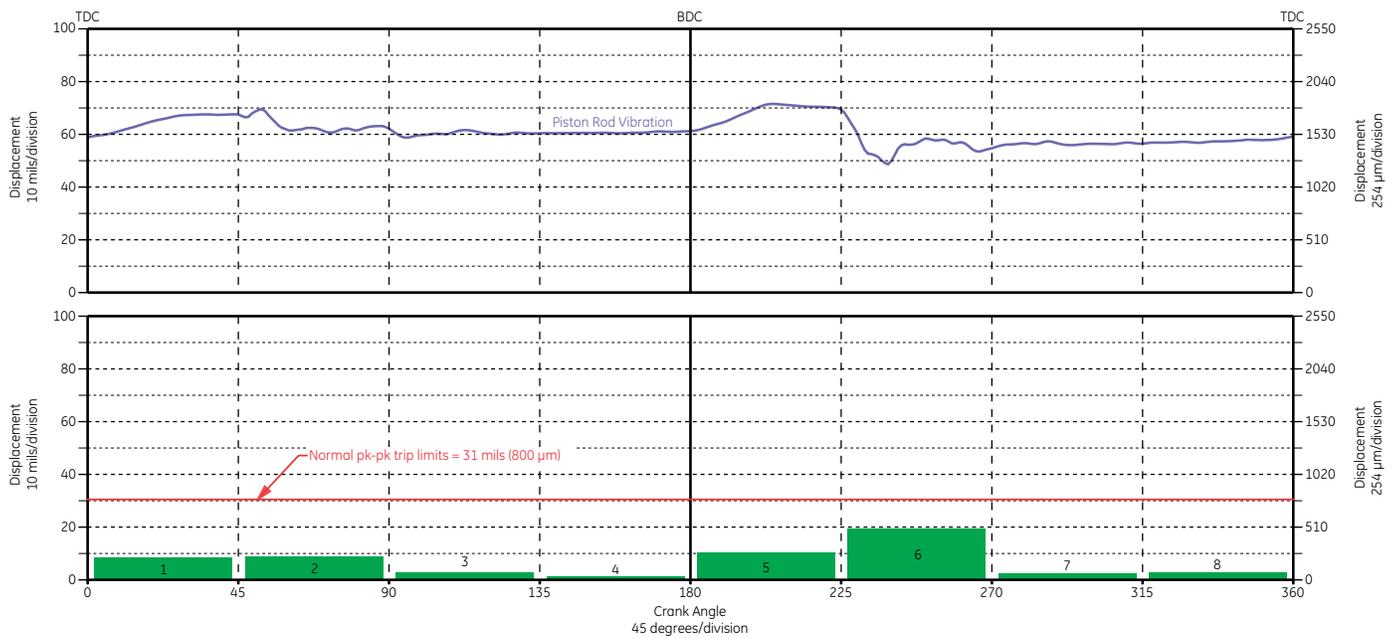


Figure 13. Stage 1 LP cylinder at 100% capacity vertical probe unfiltered piston rod vibration and segmental vibration analysis (March 11, 2008 at 07:47:05), prior to shutdown.

Conclusion

Segmental vibration analysis does have value in reciprocating compressor monitoring strategy. However, in the specific instance of unfiltered piston rod vibration monitoring as a shutdown function, the data indicate that this methodology provides insufficient rigor to automatically shut down a compressor when applied to API-618 style compressors in refinery and petrochemical service.

While this paper applies specifically to API-618 compressors, compressor configurations and styles outside of this specification, for example hyper compressors with brittle tungsten carbide rods, exist in which unfiltered piston rod vibration does provide reliable protection. For questions about a specific application, please contact your local sales representative.

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